Trees (2017) 31:919–928
DOI 10.1007/s00468-016-1517-z

ORIGINAL ARTICLE

Growth response of Scots pine to changing climatic conditions over the last 100 years: a case study from Western Hungary

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Received: 3 June 2016 / Accepted: 23 December 2016 / Published online: 25 January 2017

Abstract

Key Message **Climate change has a significant influence on the climate-growth relationship of Scots pine in Western Hungary, and this typically expressed as a decrease in the strength of the connection between tree-ring width variation and climate data**.

Abstract This paper aims to expand our understanding of the climate-growth relationship of Scots pines in Transdanubia. Changes in the influence of climate on tree growth over various time-scales have been the subject of numerous investigations with pine trees, but these relationships have never been explored for Scots pines in Hungary. In this research, Pearson correlation values in 25-year moving windows were used to evaluate the temporal relationships of temperature, precipitation and tree-ring width variation, and additionally to investigate how these might be connected to climate change between 1915 and 2014. In the cases of summer precipitation and late winter-early spring temperature, our results detected a significant positive influence on the tree-ring width development of those Scots pines at our study sites. Furthermore, intensive warming over the last 100 years has resulted in a changing relationship between tree-ring width variation and climate data. In this study, the temporal instability of the climate-growth relationship was observed in every important month of tree-ring growth, and the response of growth to climate declined sharply in most of the studied periods. This indicates that ongoing climate change has already altered the climate-growth relationship in Scots pines in certain sites of Western Hungary.

Keywords Dendroclimatology · Climate change · Climate-growth relationship · Moving window correlation

Introduction

Climate change, together with its side effects, has significant influence on forest ecosystems. For example, warming can modify the onset of the growing season (Koprowski 2013), its extension (Menzel and Fabian 1999) and the dynamics of tree-ring formation during the active period (D'Arrigo et al. 2008; de Luis et al. 2014). Increasing temperature has already caused measurable changes in the larger region in which our sample sites are located. In Slovenia, de Luis et al. (2014) reported a warming trend and noted that the long-term increase in spring temperatures limits growth in most tree species, thereby having a negative impact on forest productivity. Investigating spruce and larch, Koprowski (2012, 2013) also found a significant degree of influence thanks to changing climatic conditions in Poland, noting that rising temperatures in February and March can decrease tree resistance to low temperatures, making them more vulnerable to late winter-early spring frosts. In contrast, Churkova et al. (2014) in their study of spruce found that a rise in temperature in spring has a positive effect on tree-ring formation in the Swiss Alps at high altitudes.

As Scots pine is among the most frequently used species for dendrochronological analysis, its climate-growth relationship has been investigated numerous times under different climatic, environmental and altitudinal conditions (Sánchez-Salguero et al. 2015; Bauwe et al. 2015; Bauwe

Communicated by S. Leavitt.

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et al 2013; Panayotov et al. 2013; Bogino et al. 2009; Pärn 2009; Eilmann et al. 2006). In relation to current climate trends, different recent and future responses have been reported and estimated. Although the capacity of Scots pine to adapt to variable climatic and environmental conditions is large, as a result of warming decreased growth trends are predicted for the species in central and southern Europe (Reich and Oleksyn 2008).

While climate change may have serious impacts in the Carpathian Basin (Parry et al. 2007; Bozó 2010), which may significantly influence the forest ecosystem, there have been few studies of the temporal alterations in the climate-growth relationship of certain tree species (e.g. on beech, Garamszegi and Kern 2014), and these are particularly lacking for pine trees (with the exception of Misi and Náfrádi 2016b). Of pine species in Hungary, Scots pine represents the largest group, and although it is not native, it plays an essential role in Hungarian forest composition (NFCSO Forestry Directorate Forest Inventory 2014). To evaluate the behavior of the tree-ring width variation of Scots pine, two well-known pine-covered sites from the western part of Hungary were selected for the study. The sites were selected with the aim of enabling the investigation of the Scots pine's climate growth relationship under similar climatic conditions but with different growth environments. While the sites are relatively close to each other, the current state of the two stands differs mainly in their divergent pedological conditions and water management regimes. The current research aims (1) to identify which climate parameters affect tree-ring width variation in our sites, and subsequently (2) to investigate how the influence of changing climatic conditions has evolved over the last 100 years and has modified the climate-growth relationship.

Materials and methods

Study site and climate data

One of our study site is Fenyőfő (FFO, N47°21′, E17°45′, 250 m a.s.l.), situated in the northern part of Western Hungary on the northern slopes of the Bakony Mtns (Fig. 1a). This forest, which is the oldest pine stand in Hungary, is growing on secondarily evolved dune sand and weakly humic sandy soil formed from a calcareous sand bedrock (Borhidi 2003). Due to the thick sand layer and intensive summer evaporation, the groundwater level usually subsides below the roots, which promotes poor water management and unfavorable conditions for tree growth. The forest is mixed, with oak (*Quercus cerris, Quercus robur, Quercus petraea*), silver birch (*Betula pendula*) and ash (*Fraxinus ornus*), but the canopy is dominated by a pine population of uneven age.

The second site is Szalafő (SZFO, N46°52′, E16°21′, 270 m a.s.l.), and is situated in the western part of the country, near to the Austrian and Slovenian borders. The pedological conditions at this site are better; the dominant soil is brown forest soil formed on Quaternary sediments. The dominant species is Scots pine, but the forest is mixed, with oak, birch, ash, beech (*Fagus sylvatica*) and spruce (*Picea abies*).

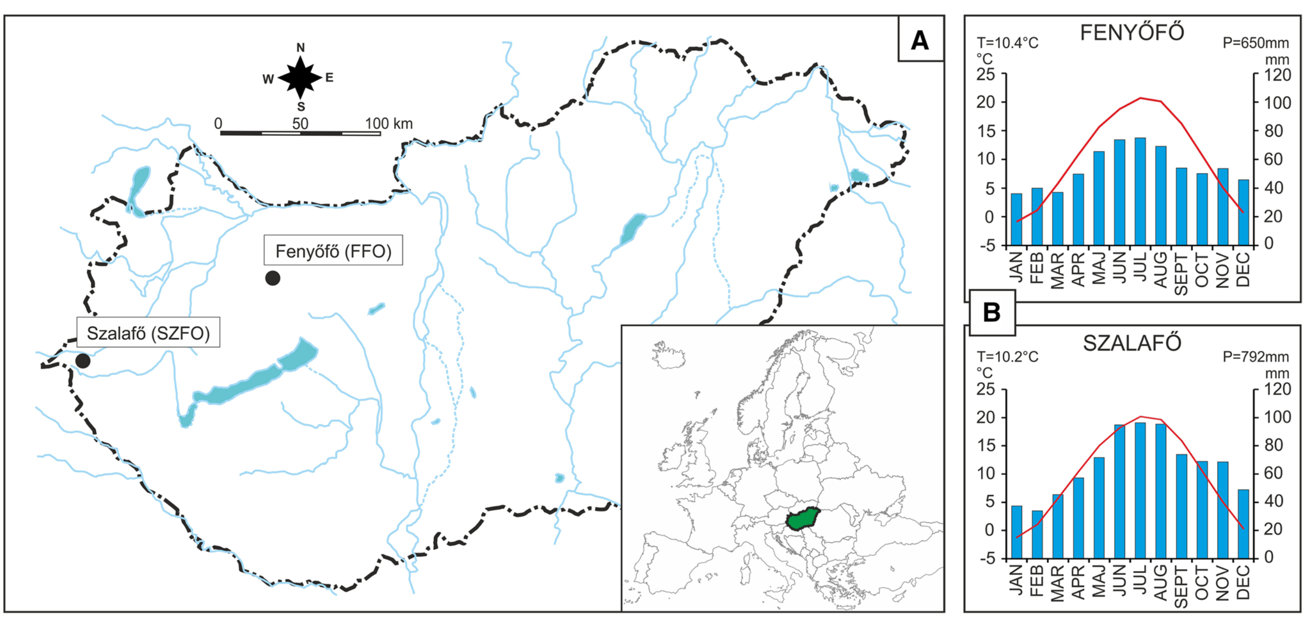

Fig. 1 Location of study sites (**a**) and long-term characteristics of temperature (*lines*) and precipitation (*bars*) (**b**)

Both areas have their precipitation and temperature maxima in summer and similar annual distributions of temperature and precipitation values. Site SZFO has higher total precipitation (~800 mm), with a maximum in July, but site FFO is warmer with its 10.4 °C long-term annual mean temperature (Fig. 1b).

Since the closest meteorological stations do not have sufficiently long instrumental meteorological data for our research, we used CRU TS 3.23 0.5°×0.5° (Harris and Jones 2015) gridded monthly and seasonal temperature and precipitation data for the period of 1915–2014. The dataset we needed was extracted for the sample areas using the KNMI Climate Explorer web page (http://climexp.knmi.nl). To check the reliability of the gridded data, it was compared to the shorter-term instrumental data already provided by stations near the study sites; a high correlation for the overlapping periods was found.

Climate over the last 100 years

According to the temperature data of sites FFO and SZFO, a remarkable warming trend started at the beginning of the 1990s. With some exceptions, the temperature of the first 75 years of our study period fell below the mean of the 1971–2000 reference period (Fig. 2), especially in the winters between 1940 and 1964, which proved to be the coldest era of the last 100 years. After 1990, however, temperature exceeded the reference period's mean in every month at both study sites. The biggest changes occurred in April, in the summer months and in November. Winters were also significantly warmer. Between 1990 and 2014 the 25-year mean of the winter months did not drop below 0 °C (except in December in site FFO).

In monthly precipitation values only small fluctuations can be observed, but seasonally and annually there are

Fig. 2 Temperature and precipitation anomalies in the last 100 years with respect to the 1971–2000 reference period, together with the aridity index for each study site. Temporal changes in aridity were investigated using a 25-year moving mean calculation for each season

significant changes. Considering months individually, April and October at both sites, and August in the SZFO site experienced the greatest precipitation decreases (Fig. 2). In the trends of seasonal precipitation data, however, a different pattern is observed. While summer precipitation has been increasing since the beginning of the 1900s at the FFO site, at the SZFO site the opposite trend is observed, with a massive decrease taking place. The mean of the first 25-year period (1915–1939), 848 mm, declined by almost 80 mm by the end of the last quarter of the study period (1990–2014: 770 mm).

It seemed likely that the small decrease in precipitation and the dramatic increase in temperature would be combined in a steeply rising aridity index. As the 25-year moving mean values of the aridity index over the last 100 years show, climatic conditions have rapidly changed at both sites (Fig. 2). Before 1990, aridity indices were typically below the 1971–2000 level in both spring and summer, and it is these seasons that are particularly important in tree ring growth. Because of the warming trend, every season's aridity index value had risen considerably above the reference period's mean by the end of our study period.

Sampling and chronology building

In the two sampling periods (in 2014 at site FFO; in 2015 at site SZFO), old, dominant, healthy trees were selected for sampling. In total, 53 individuals were cored at breast height, and two samples were taken at 180° to each other in each tree. All of the samples were air-dried, then sanded and polished with 8 different sandpapers to enhance tree-ring structure. The measurement of tree-ring width was performed using a LINTAB Measurement Station, at 0.01 mm precision, from the pith to the bark (Rinn 2003). Rings formed before 1915 were excluded, which marks the beginning of our study period. The on-screen crossdating of individual series was done using the TSAPX and TSAP-Win programs. Series intercorrelation, missing ring identification and the detection of possible dating errors were checked using the COFECHA program (Holmes 1983).

Climate signal

Because of the trees' age, size and the effects of stand dynamics, several non-climatic trends are preserved in tree rings, and these need to be removed. All of the series were, therefore, standardized by fitting a cubic smoothing spline with a 50% frequency response at 67% of the length of the individual series (Cook and Peters 1981). Autocorrelation was removed from each individual index, then all the detrended residual series were averaged into a site chronology using the biweight robust mean (Cook 1985).

The stability of the common signal preserved in the index series was determined by calculating the Expressed Population Signal (EPS), which was applied with a 25-year window lagged by 1 year using the widely accepted threshold of 0.85 (Wigley et al. 1984). In addition, the mean interseries correlation (Rbar) was computed using the same window and lag as the EPS values. Standardization and index calculation procedures were carried out using the ARSTAN program (Cook and Krusic 2006).

To evaluate the connection between climate data and tree-ring indices, Pearson correlation coefficients were calculated from May of the previous year (MAY) to October of the current year (Oct) of tree-ring formation. Not only were individual months analyzed, but all seasonal and annual data as well. For the investigation of the effect of changing climatic conditions on tree-ring growth during the study period, 25-year moving window correlations of meteorological and tree-ring width data were computed. Only those months and periods were considered in which precipitation or temperature had significant or near-significant correspondence with tree-ring indices in the whole time-span of the study.

Not only were precipitation and temperature individually examined, but an aridity index (AI) was also calculated to highlight the influence of drought conditions on tree ring-width variability. Calculations were carried out using precipitation and temperature anomalies according to the following formula

$$\mathrm{AI} = \left(\left(T - T_{\mathrm{m}}\right)/T_{\mathrm{d}}\right) - \left(\left(P - P_{\mathrm{m}}\right)/P_{\mathrm{d}}\right)$$

where T is the temperature, T_{m} is the mean temperature of the reference period (1971–2000), T_{d} is the deviation of the reference period temperature, P is the precipitation, P_{m} is the mean precipitation of the reference period, and P_{d} is the deviation of the reference period precipitation. The values of this index are positive in the case of drought events. Computation was made for every month of the current year of tree-ring formation, for all seasons and for annual data. AI values were tested against meteorological data using the Pearson correlation.

Results

Tree-ring chronologies

Two site chronologies were developed: one for the FFO site derived from the tree-ring widths of 19 trees, and another for the SZFO site comprising the data from 34 trees. The raw chronologies show a high level of similarity to each other, with a correlation of $r = 0.66$. Only small differences are to be found in the most common statistical indicators, such as standard deviation, mean segment length, series intercorrelation and autocorrelation (Table 1). The site chronology for FFO starts with 5 trees in 1915 and reaches its replication maximum in 1982. Replication in the SZFO chronology begins with 10 cored trees at the beginning of the record and reaches its maximum in 1960.

Climate-growth relationship

Expressed population signal (EPS) values indicated a stable and strong common signal in both sites. Values are above the widely accepted 0.85 threshold, and exceed the currently recommended higher critical level (ca. 0.90) (Mérian et al. 2013) as well (Fig. 3e). Similarly to the case of EPS, mean interseries correlation (Rbar) also indicates strong relationships between the individual series, with averages of 0.43 (SZFO) and 0.44 (FFO). These results suggest that both chronologies carry a reliable climate signal and are suitable to represent the whole pine stand.

According to the results of a correlation analysis between tree-ring indices and climate data, growth at our sites has corresponded well to meteorological conditions. Considering the months individually, precipitation in June and July has the biggest positive impact on tree-ring width variation, but over a longer time-scale, the total precipitation of summer has the greatest effect (Fig. 4). The greatest influence of temperature is negative in August, but the correspondence is positive in February and March. Although temperature plays a secondary role in the development of tree-ring widths, its influence on available precipitation is particularly important. The connection between tree-ring data and the aridity index shows the greatest degree of negative correlation in the merged summer period (Fig. 4). It is also notable that in winter, higher aridity values play a positive role in Scots pine tree-ring width at our sites.

The moving window was employed to determine how the changes in climatic conditions over the last 100 years have affected the variability of tree-ring width on a long time-scale. Early in these 100 years, temperature had a significant effect on ring width variation in most of the examined periods, but the temporal stability of each signal proved to be weak. In parallel with the accelerating warming at the study sites, the significance of the relationship between temperature and tree-ring widths vanishes. The biggest decrease in correlation between annual increment and temperature occurred in March, but the strength of relationships also declined in July and in the winter period (Fig. 5). It is important to note that the sites were affected differently. For example, in July at the FFO site, temperature never exceeded the significance level, so the decrease in correlation had less impact. In the case of precipitation, high degree of instability was detected in the signal. Since the analysis of the individual month of July showed the highest correlation with tree growth over the whole study period, it is surprising that the strong connection that existed in the first part of the 100-year period falls below the level of significance by the end of the record. On a seasonal scale, however, the impact of precipitation persisted, thanks to the increasing trend in the correlation values of June rainfall, and even August precipitation at the SZFO site.

Discussion

In parallel with international trends (Luterbacher et al. 2004; Xoplaki 2005; Parry 2007; de Luis et al. 2014; Koprowski 2012), the climate of our study sites in Western Hungary has changed significantly over the last 100 years, which has already remarkably impacted the pine forests (Gulyás et al. 2014; Misi and Nádrádi 2016a, b), and this process will most probably continue in the future (Bozó 2010; Náfrádi et al. 2013). The climate-growth relationship observed in the tree-ring indices of our study sites is typical of areas of low elevation-moderate climate with a positive dominance of summer precipitation and a negative maximum correspondence with summer temperature. Similar behavior of such parameters had earlier been reported from Hungary in the case of other species too (e.g. Garamszegi and Kern 2014; Kern et al. 2013), and has been experienced outside of Hungary in the case of Scots pine (e.g. Michelot et al. 2012; Panayotov et al. 2013) and other conifer species (e.g. Koprowski 2012, 2013; Bijak 2010), all cases under similar climatic and environmental conditions to those at the sites. Our results indicate the amount of July precipitation is the most important limiting factor in tree-ring growth over the entire study period. In August and especially in June rainfall also correlates significantly, but with lower weight. Although the previous years' climatic conditions are usually essential for tree growth in the current investigation, only the precipitation of the previous

Table 1 Dendrochronological statistics for the two Scots pine chronologies

Site name	Lenght	No. of trees	CwM	MRW (mm)	MS	SD	AC1	MEPS	MRbar
Fenyőfő (FFO)	1914–2013	19	0.651	2.36	0.234	1.168	0.785	0.97	0.44
Szalafő (SZFO)	1915–2014	34	0.637	2.62	0.224	1.382	0.832	0.96	0.43

CwM Correlation with master, *MRW* mean ring width, *MS* mean sensitivity, *SD* standard deviation, *AC1* first-order autocorrelation, *MEPS* mean EPS, *MRbar* mean Rbar

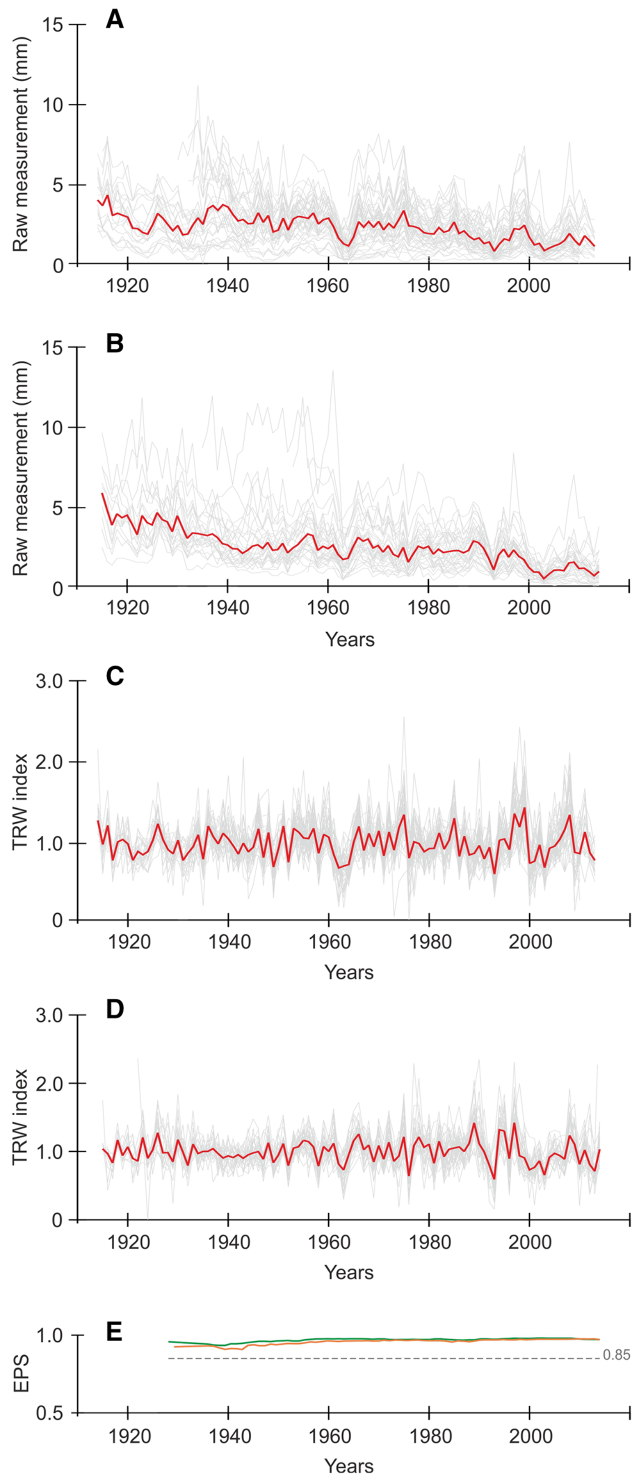

Fig. 3 Raw (**a, b**) and residual (**c, d**) chronologies of site SZFO (Szalafő) and FFO (Fenyőfő). EPS values (**e**) indicate the stability of the climate-related signal in the tree-ring series, the *horizontal dashed line* marks the widely-accepted 0.85 threshold

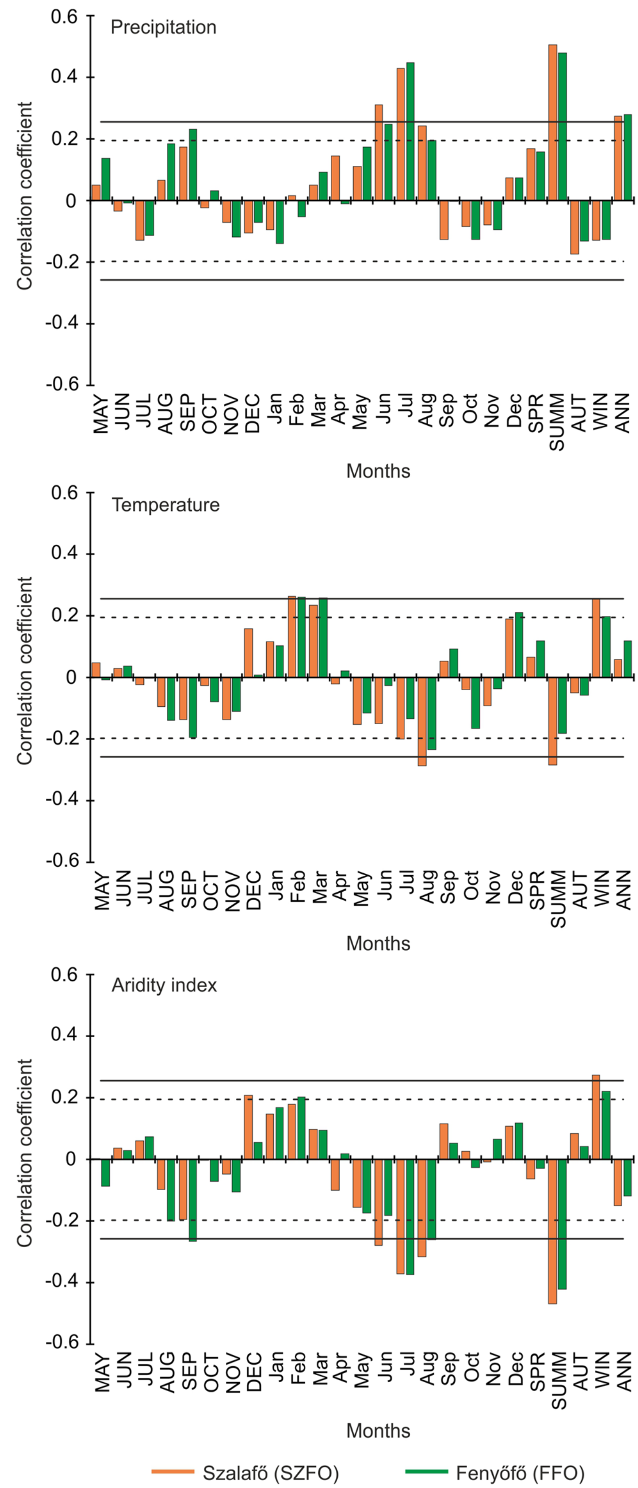

Fig. 4 Pearson correlations between precipitation, temperature, the aridity index and residual tree-ring data. The *dashed* ($p < 0.05$) and *solid* ($p < 0.01$) *horizontal lines* indicate the significance level

September was significant at the FFO site. Temperature, with its negative effect on tree-ring formation, dominates in August, but its importance is lower than had been expected, especially at the FFO site, where the role of seasonal summer temperature did not exceed the significance level ($p < 0.05$) (Fig. 4). The effect of temperature on tree growth

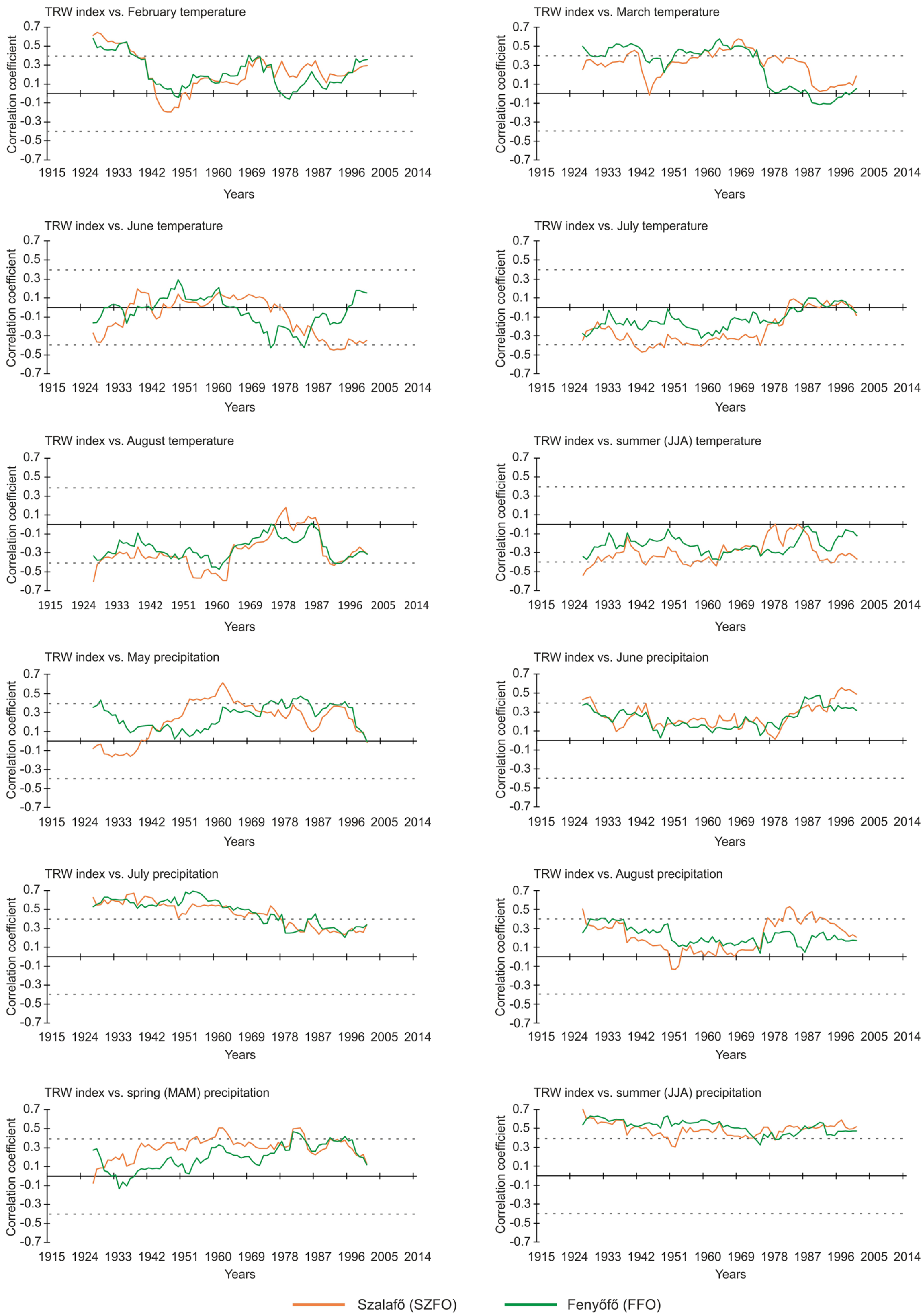

Fig. 5 Results of the 25-year moving window correlation between tree-ring width variation and climate data in different periods of the year. *Horizontal dashed lines* indicate the $p < 0.05$ significance level

is highlighted to a much greater degree in the correlations with the aridity index. In this case, almost all the summer months are above the significance level (the only exception being June at the FFO site). This result shows that summer temperature has a particularly important role in tree-ring width variation, in particular due to its influence on the usable amount of precipitation. In addition to summer, a significant relationship between temperature and tree-ring widths can be found in February and March. This result is very unusual because no other papers have reported a similar pattern in Hungary (e.g. Kern et al. 2009, 2013; Garamszegi and Kern 2014). However, it is important to note that these studies were performed on beech and oak. From the region in which the country lies, some authors have observed a similar relationship for larch (Koprowski 2012, 2013), for black pine (Poljanšek et al. 2013) and for spruce trees (Bošel'a et al 2013), but generally from areas with a different climate or at a higher elevation. This positive influence in the late winter-early spring period can most probably be explained by the essential role of temperature in the onset of tree-ring formation.

The temporal stability of the climate-growth relationship of different tree species has been investigated numerous times (e.g. D'Arrigo 2008; Pärn 2009; Koprowski 2012, 2013). At our sites, it is the changing conditions of late winter-early spring and summer, which are contributing to the changing response. In spite of the increasing temperature, its role in tree-ring growth has been decreasing since the middle of the 20th century. The greatest decline has occurred in the case of February and March, when a strong positive relationship ($r > 0.4$) was observed in the first part of our study (Fig. 5). In parallel with the intensive warming, correlations in both months started to decline, and the temperature of February and March has become an insignificant factor in terms of tree-ring width variation. Koprowski (2012, 2013) found the same reaction to warming conditions in the late winter-early spring period in conifers in the lowland area of Poland. In those papers, he notes that because of increasing temperature not only can the correlation between tree-ring growth and temperature disappear but the warming can have a side effect that significantly alters normal tree-ring development in the form of a decreased resistance to low temperatures. This occurs as a result of higher temperatures disturbing the hardening of trees, so that they become more vulnerable to late winter-early spring frosts. A similar process has been observed at high northern latitudes as well (Briffa et al. 1998), where summer temperature is the main limiting factor of tree growth. According to tree-ring widths and density data, increasing temperature after the 1950s caused a weakening response between conifers' tree-ring growth and mean summer temperatures (Jacoby and D'Arrigo 1995; Wilson and Luckman 2003; D'Arrigo et al. 2008). This phenomenon is called the "divergence problem". Although there are still questions concerning the exact mechanism of this phenomenon, D'Arrigo et al. (2008) have noted that temperature alone is not always sufficient to characterize the trees' thermal environment, since they will also be influenced by other factors such as soil moisture, soil temperature or insolation. At our sites we also observed a decline in the correspondence between temperature and tree-ring width variability in August and especially in July (Fig. 5). June is the only summer month, particularly at the SZFO site, whose influence on tree-ring width increased. Summer temperature was not alone in experiencing a reduced correlation. Over the first half of the last century, winter temperature had a relatively stable positive connection with our Scots pine ring width indices, but by the end of the 1990s this had completely disappeared; moreover, for a short period the relationship almost became significantly negative at the FFO site.

In general, the amount of precipitation in every month and season decreased in our moving window analysis, but this generated different correspondences with Scots pine tree ring-width variations. For example, decreasing rainfall in May, June, August, and in spring resulted in stronger correlations with tree-ring width indices, which may be a byproduct of the drastic decline in the relationship of July precipitation and tree-ring growth. Since July precipitation was the most important factor for tree-ring width development in most of the last 100 years, the weakening of its role may have enhanced the importance of other periods' precipitation conditions. The correlation of both June and August precipitation exceeded the significance level, whereas July fell beneath it (Fig. 5). Consequently, a remarkable degree of correlation decline occurred in what had been the most important month, but a stable positive correlation remained for the summer period as a whole. At the same time, the improved correlations with June and August precipitation did not affect both sites equally and to all appearances does not seem set to persist. The August correlation had dropped below the significance level by the end of the 1990s, and currently it looks like June is showing a decreasing trend as well.

The effect of changing climate on the climate-growth trends of Scots pine in our study sites is, therefore, clearly visible. Bauwe et al. (2015) note that in northern Germany the reduced growth of Scots pine tree rings will probably be moderate in the future if the positive effect of increasing winter temperatures is able to counterbalance the negative effect of summer droughts. Although that study was performed under similar climatic and environmental conditions to the current one, at our sites no increasing positive effect of winter temperature could be observed on tree-ring width development, which seems to forecast a continuing negative influence of warming and more frequently occurring droughts on growth dynamics and tree-ring width variation.

Conclusion

The aim of this study was to investigate climate parameters that are the main limiting factors on the tree-ring width development of Scots pine, and to evaluate the temporal stability of the climate-growth relationship in the light of climate change over the last 100 years. Our results indicate that rising temperatures and decreasing precipitation experienced in Hungary will alter tree growth drastically. The formerly dominant role of July precipitation as the most important limiting factor in tree-ring width variation has been supplanted by June and August rainfall. However, a further decline in precipitation may, in turn, change the importance of these as well. In spite of rising temperatures, the role of temperature in both the late winter-early spring period and summer has been declining. The same process has been observed in the case of conifers in Poland by Koprowski (2012, 2013) and also at high latitudes by numerous authors (e.g. Briffa et al. 1998; Vaganov et al. 1999; Briffa 2000; D'Arrigo et al. 2004).

Author contribution statement Dávid Misi conceived the structure and idea of the paper, carried out the main part of the sample and data collection, data analysis and writing of the paper. Katalin Náfrádi contributed to the sample collection and in the writing of the paper.

Acknowledgements The authors would like to express their gratitude to Ms. Rita Márkus and to Mr. Szabolcs Borka for their invaluable help during sampling, and to Mr. Zoltán Kern for organizing the sample preparation and measurement. We also would like to thank the two reviewers and the editor of this paper for their valuable advice and comments.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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